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Leptoproduction of Heavy Quarks in the Fixed and Variable Flavor Schemes*

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ABSTRACT

We compare the results of the fixed-flavor scheme calculation of Laenen, Riemersma, Smith and van Neerven with the variable-flavor scheme calculation of Aivazis, Collins, Olness and Tung for neutral-current (photon-mediated) heavy-flavor (charm and bottom) production. We compare the structure function $F_2(x, Q^2)$ throughout phase space, and also analyze the μ-dependence We find that the former calculation is most applicable near threshold, while the latter works well for asymptotic Q^2.

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LEPTOPRODUCTION OF HEAVY QUARKS IN THE FIXED AND VARIABLE FLAVOR SCHEMES ‡

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1. Motivation of Variable and Fixed Flavor Schemes

Several experimental groups have studied the semi-inclusive deeply inelastic scattering (DIS) process for heavy-quark production $\ell_1(\ell_1) + N(P) \rightarrow \ell_2(\ell_2) + Q(p_1) + X(P_X)$. Most analyses of this process assume that the hadron is comprised of only the massless gluon , up, down, and strange quarks, while the charm, bottom, and top quarks are treated as massive objects which are strictly external to the hadron. This view of the heavy quarks as external to the hadron is appropriate when the energy scale of the process $\mu_{\rm phy}$ is not large compared to the mass of the heavy quark, *i.e.* $M_Q \lesssim \sqrt{s}$. With new data from HERA, we can investigate the DIS process in a very different kinematic range from that available at fixed-target experiments. In this new realm, the important question is: Should the c and b quarks be considered as partons, or as heavy objects extrinsic to the hadron? Given that HERA extends the kinematic reach of the DIS process by two orders of magnitude, we can not expect our assumptions that were valid for fixed-target processes to hold in a completely different kinematic regime.[1]

Aivazis, Collins, Olness and Tung (ACOT) have discussed this issue at length in reference[2] and approach the problem by invoking the *variable flavor scheme* (VFS), which varies the number of partons according to the relevant energy scale $\mu_{\rm phy}$. The fundamental physical insight to the VFS is that in the region $M_Q \gg \mu_{\rm phy}$, the heavy quark should be *excluded* as a constituent of the hadron as it is kinematically inaccessible and decouples from the physics. However, when $M_Q \ll \mu_{\rm phy}$ the heavy quark should be *included* as a parton since M_Q is insignificant compared to $\mu_{\rm phy}$. Although the physics is unambiguous in these kinematic extremes, most experimental data lies in

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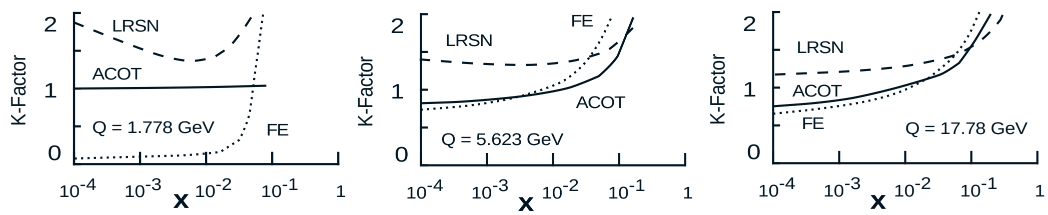

Fig. 1. The K-factor for the structure function $F_2(x, Q^2)$ vs. x for charm production.

between these clear-cut regions. In the intermediate region, the renormalization scheme of Collins, Wilczek and Zee (CWZ) provides a well-defined transition between these two extreme kinematic domains.

The above issue of what constitutes a parton also points to an inconsistency between traditional charged-current and neutral-current heavy-quark production calculations.[2] When considering charged-current processes, one begins with the purely electroweak process $W + q \to Q$. For neutral-current processes, the traditional approach is to begin with the $\mathcal{O}(\alpha_s^1)$ process $\gamma^* + g \to Q + \overline{Q}$ As we work in the new kinematic regime spanned by HERA, the concept of a "heavy" quark becomes a relative term, and traditional distinction between the charged-current and neutral-current calculations should vanish. ACOT implements the CWZ renormalization and treats both charged-current and neutral-current heavy-flavor production in a consistent fashion.

Laenen, Riemersma, Smith and van Neerven (LRSN) have calculated heavy-quark production for DIS photon exchange, beginning with the $\mathcal{O}(\alpha_s^1)$ photon-gluon fusion process and including the complete $\mathcal{O}(\alpha_s^2)$ radiative corrections in reference.[3] LRSN assumes there are no heavy-quark constituents to the hadron. For example, in producing c quarks, LRSN invokes only the g, u, d and s partons.

2. Comparison of Variable and Fixed Flavor Schemes

In Figure 1 we compare the F_2's vs. x at fixed Q. We refer to the curves as FE for the $\mathcal{O}(\alpha_s^0)$ flavor excitation process, FC for the $\mathcal{O}(\alpha_s^1)$ flavor creation process, ACOT for the complete VFS calculation and LRSN for the complete FFS calculation. The FC curve is not shown as this is the denominator in the definition of the K-factors. (Trivially, $K_{FC} = 1$.)

For $Q = 1.778\, GeV$, the FE K-factor essentially vanishes as the "heavy-quark" partons should not contribute at low energy scales. The ACOT K-factor approximately reduces to the FC result in the low energy limit. In this low Q-region, the LRSN calculation is the most appropriate.

At $Q = 5.623\, GeV$, the very fast evolution of the FE result makes it unreliable for predicting heavy-quark production. The ACOT K-factor now deviates from unity as the fast evolution of the heavy quark in the threshold region (due to abundant gluons) generates important contributions at relatively low values of Q. However the subtraction prescription ensures the result is reliable (in contrast to the FE process). The LRSN K-factor decreases at small x, and flattens slightly.

At $Q = 17.78\, GeV$, the FE, ACOT, and LRSN results have similar shapes. The K-factors are all monotonically increasing vs. x. In the range above $Q = 17.78\, GeV$, the general characteristics are similar.

In Figure 2 we compare the F_2's vs. μ at fixed $\{x, Q\}$. For all values of Q, the FE

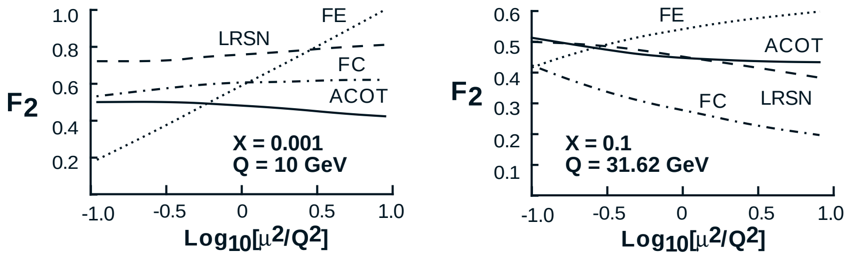

Fig. 2. The structure function $F_2(x, Q^2)$ vs. μ for charm production.

process is increasing with μ due to the increasing heavy-quark PDF. In contrast, the $\mathcal{O}(\alpha_s^1)$ FC process (driven by gluons) is decreasing with μ largely due to the decrease in $\alpha_s(\mu)$. The two-order calculations (ACOT and LRSN) that have compensating contributions to cancel out some of the μ-dependence. Specifically, ACOT combines pieces of the FE and FC processes (together with a subtraction term) to yield a result that has substantially less μ-dependence than either result in the large Q region. LRSN effectively has the $\mathcal{O}(\alpha_s^2)$ FE contribution as the collinear heavy-quark part of phase space is included, negating some of the μ-dependence of the FC channel.

3. Conclusions

We have outlined the features of both the VFS (ACOT) and the FFS (LRSN) calculation. We summarize the highlights below. While the flavor excitation (FE) process can closely match the two-order results with a judicious choice of the scale μ, the large scale dependence makes this unreliable. Likewise, while the flavor creation (FC) process is a good starting point in the threshold region. However, the LRSN calculation indicates that the corrections to this naive estimate can be large. In the threshold region, the FFS (LRSN) calculation yields the most stable and reliable results due to the domination of flavor creation. In the asymptotic region, the VFS (ACOT) calculation provides the best results because of the dominance of the collinear heavy-quark contribution. Furthermore, the ACOT result demonstrates that the heavy-quark PDF's can yield significant contributions at relatively small scales, (*i.e.* $\mu/M_Q \sim 3$).

We note that the difference between the LRSN and ACOT calculations above threshold is suggestive of higher order contributions yet to be included. As such, the results of this comparison indicate that a combining of the LRSN and ACOT calculations in a consistent fashion (with the additional mass factorizations required) should allow us to make predictions based upon a three-order result that combines the best attributes of both calculations. The result should be a calculation that will provide an important test of pQCD when compared with the results from HERA.

References

1. For a more complete set of figures and references, see: F.I. Olness, and S. Riemersma, SMU-HEP/94-21.
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